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COLORIMETRY AND ITS RELATION TO PHOTOMETRY

(A lecture delivered to the Photometry Section of the Illuminating Engineering Society on 24th November, 1936)

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EXPLANATORY NOTE

The lecture necessarily included much previously published matter, and the following account has been abbreviated by the partial or complete omission of some sections. For the convenience of those who may not be fully conversant with the subjects thus dealt with a short list of papers, in which those subjects have been treated by the lecturer or his colleagues, is appended. On the other hand the theory of physical colorimetry is given more fully here than was possible, owing to lack of time, on the occasion of the lecture.

It is unnecessary for me to explain to an audience of illuminating engineers that the colour as well as the photometric intensity of light depends on the amount and the spectral distribution of energy of radiation.

But although difference in spectral energy distribution is responsible for differences in colour there is not a separate colour for every different energy distribution. The same colour may be produced by an infinite number of stimuli all differing in spectral distribution.

This is a matter of common knowledge to photometrists. You are all accustomed to the device of using a colour filter with a filament lamp to get light of the same colour as that given by, say, a sodium, neon, or mercury discharge lamp. In all of these cases you have very dissimilar radiation on opposite sides of the photometer, yet you get the same colour. The problem of colorimetry is to identify and measure the property or properties possessed in common by all the various stimuli which may produce light which appears identical in every respect. It includes, therefore, the problem of photometry, which is to identify and measure the property possessed in common by all stimuli which produce light identical in the one respect of brightness.

Since the criterion to be satisfied is visual identity, the measurements must be based on visual matching. In attempting to cover the ground in a single lecture, it is necessary to cut every long story short, so I will just say that the only kind of visual match by which the necessary information can be obtained is the kind in which we match the light under test by a mixture of three standard stimuli, fixed in colour, but variable in intensity. An instrument constructed for the production of such matches is called a trichromatic colorimeter, and the simplest way of getting quickly into the heart of our subject will be to describe such an instrument and explain how it is used.

Here followed a description of the trichromatic colorimeter recently designed by Donaldson (Proc. Phys Soc., 1935 (47), 1,068), and an explanation of how such instruments are used to obtain for the colour of any specimen under test a numerical expression of the form

$$S = \alpha R + \beta G + \gamma B$$

where $\alpha + \beta + \gamma = 1$, negative values of any of the *trichromatic coefficients* α, β or γ being possible. R, G, and B denote the three standard stimuli of the colorimeter. This expression is termed a *unit equation*, and its significance is that a quantity designated a *trichromatic unit* of the test stimulus, S, is equal in brightness and colour to a stimulus built up from the stimuli R, G, and B, also measured in trichromatic units, in the proportion $\alpha : \beta : \gamma$. The practical significance of negative coefficients was explained.

There is no unique virtue associated with any particular red, green, or blue stimulus as the instrumental standards. The method of use of the instrument, and the principles on which the results are treated would be the same whatever three colours were used as standards. The use of fairly saturated red, green, and blue standards is, however, usual in all trichromatic colorimeters, as it has the practical advantage that a larger proportion of the colours of commerce can be matched directly without transferring any of the standards to the test side of the field. In principle, however, the standards of a trichromatic colorimeter may be of any three colours we choose, and we can determine, by the methods we have just discussed, a unit equation in terms of these standards for any light whatever. All the quantities occurring in such equations are algebraically additive, so that from the unit equations of any group of stimuli we can calculate the effect of combining them in any desired quantities.

We must now examine the significance of the trichromatic unit of quantity. The photometrist is accustomed to evaluating quantities of light in accordance with the criterion that when the two sides of a photometric field appear equally bright, the quantities of light per unit area of the fields are equal. In the case of lights of different colours he may use special devices such as flicker photometers or specially calibrated photoelectric apparatus to avoid the difficulties of making a precise match of brightness; but all such devices are intended to give results in accordance with the equality of brightness criterion.

Now it is obvious that when we have two stimuli of the same colour-quality, quantities which are equal when expressed in trichromatic units must also be equal in photometric units, because we have a complete match both in colour and in brightness. But in the case of stimuli of different colour-qualities the trichromatic scales of quantity and the photometric scales will not correspond. In order that we may be able to calculate the colour relations of quantities of light which have been measured photometrically, or

vice versa, we must know the relation between the colorimetric and photometric units.

Our trichromatic units are defined by treating as equal the amounts of the three instrument standards which match a standard white, but these quantities may be very far from equal in brightness. We can correlate the two methods of defining quantity as follows. If we measure in photometric units the relative luminosities of the light admitted to the colorimeter field for known settings of each of the shutter scales, we can calculate from this the relative luminosity corresponding to one division of each scale. By introducing the *white light factors* (which relate the scale units to trichromatic units). we can then calculate the relative luminosities of one trichromatic unit of each of three standard stimuli. I need not go into how this is done, as it is a fairly simple problem in heterochromatic photometry.

Suppose that these luminosities are in the ratio $L_r : L_g : L_b$, and consider our typical unit equation

$$S = \alpha R + \beta G + \gamma B$$

which tells us that one trichromatic unit of the stimulus S is exactly matched by α units of R, β units of G and γ units of B. In order to express the same fact in photometric units we must multiply each trichromatic quantity by its appropriate luminosity factor. Denote the luminosity factor of the stimulus S by L_s, then our equation becomes

$$L_sS = \alpha L_rR + \beta L_gG + \gamma L_bB$$

Since our equation represents a complete match in colour and brightness, the total brightness on each side of the equation must be the same, so

$$L_s = \alpha L_r + \beta L_g + \gamma L_b.$$

From this relation we are able to compute the luminosity factor L_s of a trichromatic unit of any stimulus S, provided we know the factors for the three standard stimuli of the instrument. We are therefore able to change from photometric units to trichromatic units or vice versa, as required by any practical problem which may arise.

From the unit equations giving the colour quality of stimuli in terms of the three standards of any trichromatic colorimeter, together with the luminosity factors of the three standards, we can solve any problem of colour mixture. But formulae and lists of figures are dry stuff, and the relations between colours are not very obvious from numerical specifications. It is useful to be able to exhibit their relations graphically, and the trichromatic method of specifying colour quality by a unit equation lends itself to this purpose.

The method of graphical representation which was universally used until comparatively recently was devised by Clerk Maxwell.

Here followed a description of Maxwell's colour triangle and the derivation from it of the more modern mode of representing colour-qualities by points on a two-co-ordinate graph on ordinary squared paper. Reference was made to the use of such diagrams for graphical solution of colour mixture problems and for exhibiting much more readily than columns of figures the relations among groups of colours. Lantern slides showed the locus of the spectral colours on a Maxwell triangle and on a rectangular plot (Fig. 1), the unit equations being in terms of the red, green, and blue standards of one of the National Physical Laboratory colorimeters.

The spectral colours, which of course merge gradually into one another, are distributed along the continuous line. The wavelengths are marked at intervals along this line. The locus is everywhere concave towards the inside and since every stimulus in nature is made up from some combination of the spectral constituents it follows from the straight line law of mixture that all possible colours must lie inside the region of the diagram bounded by the curved locus and the straight line joining its extremities. Conversely any colour-quality inside this area is possible for stimuli of suitable spectral composition.

Another notable point is that the spectral locus is everywhere outside the colour triangle for the three standards, so that no spectral colour can in fact be accurately matched by any mixture of these standards. All the unit equations have a negative coefficient. This is true whatever set of three stimuli we use as standards in our colorimeter. We see, however, that for the portion of the spectrum from the red end to the yellow-green region of wavelength about 0.54μ the locus is nearly straight, and is very close to the RG side of the triangle. Any combination of constituents from this range of the spectrum will produce colours which, from the straight line law of mixture, lie close to the spectral locus and so will be almost indistinguishable in appearance from spectral colours.

This explains why it is so easy to obtain materials with bright highly saturated colours in the red, orange, yellow, and yellow-green group.

On the other hand, the marked curvature of the locus from the green to the blue regions of the spectrum makes it impossible to get a colour near to the spectrum locus without restricting the stimulus to a fairly narrow range of wavelength. That is to say, in order that a coloured material shall have a highly saturated colour in the blue-green range, it must absorb all except a short region of the spectrum. It must, therefore, absorb most of the light, and will, in consequence, be a very dark material. Not only so, but with reflecting materials there is always some light reflected which has penetrated only very slightly, if at all, into the absorbing medium, so it is very difficult to confine reflected light to a very narrow spectral region. This is why we rarely find highly saturated blue-greens among the colours of objects. Thus the important looking region of the diagram which bulges outside the G.B. side of the triangle is not very important in practice because we do not often find colours in this region among the materials of commerce. Most commercial colours lie inside the triangle R.G.B. and can be matched directly by a mixture of these three standards. This is the reason for choosing standards of these particular colours in the National Physical Laboratory colorimeters.

We must bear in mind that the colour triangle is a diagram. It is not, as some people imagine, a coloured chart containing colours with which to match other

samples. It is simply a graphical representation of the quantities obtainable by colour measurement.

It is possible, however, to produce a real colour triangle such that the colour at any point is actually of the colour-quality corresponding to the position of that point on the Maxwell triangle. Such a device is not of any practical utility, but it is interesting to see it as it illustrates rather strikingly the way in which an infinite gradation of colours can be produced from three constituents. I have brought along an apparatus which we use for demonstrations to visitors at the Laboratory. The details of the apparatus are irrelevant and I will not waste time in describing them. The important thing is that it projects three beams of light, red, green, and blue, on a triangular area of a screen and that each of these beams is most intense at one corner of the triangle and diminishes to zero along the opposite side. At any point within the triangle the intensity of, say, the red light, is proportional to the distance from the side opposite the red corner. Similarly for the green and the blue. The light at any point inside the triangle is therefore made up of the red, green and blue in quantities proportional to the distances from the sides, and is therefore of the colour which is represented by that point on Maxwell's triangle. Of course we cannot project negative amounts of the standards, so we are unable to show the colour distribution outside the triangle. You see that we get very good yellows and oranges, of high saturation, along the Red-Green side of the triangle, but that the colours along the Blue-Green side are not nearly so convincing. Another feature exhibited is the variation of the luminosity factors of trichromatic units of different colour-quality. At all parts of the triangle the light is of equal intensity in trichromatic units, but the disparity in brightness of different regions is marked, especially towards the blue corner.

It will be clear from what has now been said that with any trichromatic colorimeter we can obtain numerical expressions for the colour-quality of light, and also relations between the quantities defining the colour and the usual photometric quantities, from which we can calculate the resultant behaviour of any combination of lights. This is all that is required, or that can ever be obtained, from any system of measurement. We must, however, see if we can relate our measurements to the physical structure of light.

Figure 2 shows another way of exhibiting the variation of the unit-equations of the spectral colours by plotting separately the values of the coefficients of R, G, and B at each wavelength. The sum of the three ordinates is always unity, and this diagram shows clearly that at no wavelength do we have three positive coefficients. The very large negative values of R occur for the blue-green part of the spectrum and correspond to the region in which the locus bulges outside the triangle in the colour diagram.

We can find the relative luminosity, in photometric units, of a trichromatic unit of monochromatic light of any wavelength, by calculating its luminosity factor from its unit equation as I have already explained. If we do this for a sufficient number of wavelengths throughout the spectrum we obtain a curve from which we can obtain the luminosity of a trichromatic unit of any wavelength. Figure 3 shows how this quantity varies throughout the spectrum.

Here followed a description of the derivation, from such data, of the so-called trichromatic mixture curves of the equal-energy spectrum—three functions of wavelength from which may be calculated the trichromatic coefficients of any stimulus of known spectral energy distribution.

We see, therefore, that we obtain a complete correlation between the physical structure of light as described by its spectral energy distribution and its colour-quality on a trichromatic system through the medium of three functions of wavelength, similar in character to the one function of wavelength which photometrists know as the visibility function, and related to the latter by the luminosity factors of the three trichromatic standards. Since the trichromatic functions and the visibility function are implicitly related, we do not need to make explicit use of the latter in calculating the photometric properties of stimuli, as we can always obtain this information from the trichromatic quantities in conjunction with the three luminosity factors of the standards.

We must not, therefore, regard the visibility function as a fourth function determining photometric values in addition to the three functions which determine colour. The three functions determine everything, the visibility function being involved in the others. It follows from the method by which the trichromatic functions are derived that the visibility at any wavelength is a linear function of the values of the three trichromatic functions, involving the constants L_r, L_g, and L_b, the luminosity factors of the standards.

It will be apparent, therefore, that from the measurements carried out on a trichromatic colorimeter we determine the photometric as well as the colour relations of stimuli. A trichromatic colorimeter is, in fact, a universal heterochromatic photometer, in which all matches are made without any difference of colour in the matching field.

We must now consider briefly how measurements made in accordance with the foregoing principles can be standardised. Although we can determine all the relations of stimuli from measurements on any trichromatic colorimeter, the utility of the measurements would be greatly restricted if we could only compare measurements made with one instrument. Fortunately this is not so. We have seen that our trichromatic method of expressing colour in terms of three standard stimuli reduces to a linear equation in three independent variables. Suppose we wish to change to another set of variables corresponding to a different set of standards. If we know the values of the new standards in terms of the old, or the values of the old standards in terms of the new, we can convert any colorimetric expression from the old system to the new. We can therefore select for standardisation purposes a set of three reference standards, then whatever may be the actual working

standards in our colorimeter we can convert the results to this reference system. They will then be independent of the properties of the actual colorimeter employed.

We have not time to deal with the theory of such transformations, but they are only special cases of the type of colour mixture problem which can be solved either algebraically or graphically. The standards selected for a reference system may be stimuli which are easily defined in physical terms, such, for example, as monochromatic radiations of specified wavelengths, and, until 1931, the National Physical Laboratory employed as reference standards monochromatic stimuli of wavelengths 0.700μ (red), 0.546μ (green), and 0.436μ (blue). These were chosen because of the ease with which they could be reproduced in the laboratory for the purpose of calibrating the working standards of a colorimeter in terms of the reference system.

We may also select reference standards which are themselves defined by any linear functions of these three, and by choosing suitable functions we may obtain a system with certain specially convenient properties. This is the device adopted by the International Commission of Illumination in 1931, when it formulated, for the first time, a standard reference system for colorimetry. It selected three standards denoted by X, Y, and Z, each of which is defined by a linear equation in terms of the monochromatic stimuli of wavelengths 0.700μ, 0.546μ, and 0.436μ. It would take too long to go into the considerations which led to the adoption of these particular standards, and I can only summarise the properties of the system. Some of these properties appear at first sight to be a little mysterious, but there is no mystery, as all the properties of the system can be derived mathematically from the laws of stimulus mixture applicable to every trichromatic system. Colour-quality on the standard system is denoted by a unit equation of the usual form:

$$S = xX + yY + zZ$$

where x, y, and z are fractional co-efficients whose sum is unity.

The ordinates of the spectral mixture curves of the equal-energy spectrum, when converted to the standard system, are denoted by $\bar{x}_\lambda$, $\bar{y}_\lambda$, and $\bar{z}_\lambda$.

A hypothetical stimulus, having an equal-energy spectrum, is adopted as the "standard white" which relates the units of X, Y, and Z, so this stimulus, or any other that matches it in colour-quality, has the unit equation.

$$S_\omega = \frac{1}{3} X + \frac{1}{3} Y + \frac{1}{3} Z$$

The first property of this system which seems peculiar is that no real stimulus has negative co-efficients in its unit equation, a property in which it differs from any system employing the actual working standards of a colorimeter. The second property which is not easy to understand is that in the new system the luminosity factors of the standards are in the ratio 0 : 1 : 0. That is to say, all the luminosity of the stimulus is carried by the Y standard. The other two, while affecting the colour-quality, do not affect the brightness. The luminosity, which, as we have seen, is, in general, a function of the values of all three trichromatic functions, is in this case dependent on the value of the Y function only. The spectral ordinate of the Y function, that is $\bar{y}_\lambda$, is therefore identical with V_λ, the ordinate of the visibility function. In this system, therefore, we have the complete visual characteristics of light determined by three functions of wavelength, consisting of the visibility function and two others which, together with it, determine the colour.

Figure 4 shows the locus of the spectral colours, which I have already shown you on the colour diagram for the working standards of a colorimeter, on the corresponding diagram for the International system. You will note that in this case the spectral locus, and therefore the points representing all other colours, lie inside the triangle XYZ, in accordance with the fact that co-efficients are never negative on this system.

We must now glance briefly at the problems presented by the differences in colour-vision of observers. You are all familiar with the difficulties caused in heterochromatic photometry by these differences. For purposes of technical and commercial standardisation the photometric standards have had to be defined in relation to a so-called standard observer defined by a standard visibility function. You have had such a standard since 1924.

Colorimetric measurements are, of course, also affected by the colour-vision of observers, though not to the same serious extent, as there are compensating factors which enter into the evaluation of colour-quality, which are absent from the ordinary methods of heterochromatic photometry. Nevertheless, colorimetric results do vary with different observers, and in order to give a definite significance to our standards, a standard observer must be defined. Such an observer is, in fact, completely defined by the values of $\bar{x}_\lambda$, $\bar{y}_\lambda$, and $\bar{z}_\lambda$, tabulated in the resolutions of the International Commission. These are shown in Figure 5. When we have defined a standard observer the results of measurements must be in accordance with this definition in order to be correct. The problem of getting the correct results from the measurements of observers who are not standard is the main practical problem of colorimetry at present just as it is the main practical problem of heterochromatic photometry.

Here the other recommendations of the International Commission of Illumination, relating to standard illuminants for the colorimetry of materials, standard conditions of illumination and observation, etc., were discussed.

I hope I have been able in this necessarily sketchy account to give you some idea of the significance of colorimetry and its intimate relation to photometry. The essential idea which I want to leave with you is that, in colorimetry, what we actually evaluate is a property of radiation which can be described by three independent functions of wavelength, and that these three functions are determined in the first instance from measurements made with a trichromatic colorimeter. The values of the three functions for any sample of light determine both its colour quality and its photometric intensity. Further, there is no other

method by which we can arrive at the three functions. They must correspond to the colour-matching properties of the eye, and so must be determined by colour matching. It is true that the functions are not unique in the sense that they can only be represented by one set of figures, for, as we have seen, they can be expressed in terms of an infinite number of sets of three independent variables; but they are unique inasmuch as the members of any one set are related by linear transformations to any other set. They all express exactly the same facts about the constitution of colours.

No method of assigning numerals to colours which cannot be directly correlated with the three trichromatic functions of wavelength, which determine the relation between the physical stimulus and its visual effects, can be regarded as colour measurement. The trichromatic colorimeter is the basic instrument from which are derived the essential relations which must be satisfied by any method of colour measurement.

When once we have obtained the three essential functions involved in the evaluation of light, we may, of course, use this information to obtain the colorimetric constants of stimuli by means other than direct colour measurement. We may use purely physical methods. Many of you have already some experience of attempting to construct a physical radiometer whose relative response to radiation of different wavelengths is proportional to the ordinates of the visibility function. Such a radiometer, if successfully constructed, would integrate the product of energy and visibility throughout the spectrum, and so would measure the photometric value of the incident radiation.

If we had three such radiometers, with spectral response functions identical with the $\bar{x}$, $\bar{y}$ and $\bar{z}$ functions of the standard observer, or with the corresponding functions expressed on any other trichromatic system, the indications of these three instruments when exposed to any stimulus would evaluate it completely both in photometric intensity and colour.

A radiometer, in the sense here used, may consist of a thermopile or a photoelectric cell used in conjunction with a filter whose spectral transmission is such that the spectral response, as indicated, let us say, by the deflection of a galvanometer, is the required function of wavelength, and we may use one thermopile or photocell with different filters in turn to obtain the values of the three trichromatic components of any stimulus.

Those of you with any experience of devising filters with specified spectral transmission curves know how difficult this is. It is almost impossible with any available materials to construct filters with the required properties throughout the whole spectrum. This part of the problem may be simplified by building up each of the three functions from the indications of several radiometers differing in spectral response. In the most general case all the radiometers employed may contribute something to each of the functions. Denote the individual radiometers by A, B, C, D . . . etc., and their responses to unit intensity of radiation of wavelength λ by a_λ, b_λ, c_λ, d_λ . . . etc. In order that we may be able to measure colour by means of these radiometers, the necessary and sufficient condition is that $\bar{x}_\lambda$, $\bar{y}_\lambda$, and $\bar{z}_\lambda$, the ordinates of the three colorimetric functions, can be expressed as linear functions of a_λ, b_λ, c_λ, d_λ, etc. It might be thought that greater generality (and therefore wider practical possibilities) would be obtained by replacing $\bar{x}_\lambda$, $\bar{y}_\lambda$, and $\bar{z}_\lambda$ in the above condition by the corresponding ordinates of the mixture curves expressed in any of the infinite number of alternative trichromatic systems, but it is clear that since the transformation equations relating values on any trichromatic systems to those on any other are linear, if the values on any system can be expressed as linear functions of a_λ, etc., this is also true of the corresponding values on all other systems. There is, therefore, no loss of generality in expressing the necessary condition in a form which leads directly to results on the standard C.I.E. system. We may write the condition

$$\alpha_1 a_\lambda + \beta_1 b_\lambda + \gamma_1 c_\lambda + \delta_1 d_\lambda + \ldots \text{ etc.} = \bar{x}_\lambda$$

$$\alpha_2 a_\lambda + \beta_2 b_\lambda + \gamma_2 c_\lambda + \delta_2 d_\lambda + \ldots \text{ etc.} = \bar{y}_\lambda$$

$$\alpha_3 a_\lambda + \beta_3 b_\lambda + \gamma_3 c_\lambda + \delta_3 d_\lambda + \ldots \text{ etc.} = \bar{z}_\lambda$$

where the constant coefficients represented by Greek letters may have positive, negative or zero values.

If we expose the radiometers in turn to a stimulus of any spectral composition and the responses are a, b, c, d, etc., it is clear that $\alpha_1 a = \int \alpha_1 E_\lambda \, a_\lambda \, d\lambda$, and so on, where E_λ is the typical term in the spectral energy function of the stimulus, and that

$$\alpha_1 a + \beta_1 b + \gamma_1 c + \delta_1 d + \ldots \text{ etc.} = \int E_\lambda \, \bar{x}_\lambda \, d\lambda$$

$$\alpha_2 a + \beta_2 b + \gamma_2 c + \delta_2 d + \ldots \text{ etc.} = \int E_\lambda \, \bar{y}_\lambda \, d\lambda$$

$$\alpha_3 a + \beta_3 b + \gamma_3 c + \delta_3 d + \ldots \text{ etc.} = \int E_\lambda \, \bar{z}_\lambda \, d\lambda$$

These integrals are respectively the total values of the X, Y, and Z functions for the stimulus. By taking the ratio of each to their sum we obtain the trichromatic coefficients, and the value of the Y function is a measure of the photometric intensity of the stimulus.

The simplest possible case of the foregoing general relation is that in which there are only three filters, A, B, and C, and where all the coefficients except α_1, β_2, and γ_3 are zero. This is the case, first mentioned, of radiometers with response curves identical in shape with the $\bar{x}_\lambda$, $\bar{y}_\lambda$, $\bar{z}_\lambda$, functions. If any of the other coefficients differed from zero we would have the case of radiometer response functions identical with the mixture curves expressed on some other trichromatic system. As already stated, however, the difficulties of filter construction with available materials make it practically impossible to obtain a reasonable approach to the theoretical requirements with only three filters. The practical problem is made less difficult by increasing the

number of filters, and so adding to the number of independent variables within the control of the experimenter.

Obviously there is not a unique set of spectral response functions (a_λ, b_λ, etc.) which will satisfy this condition at all wavelengths. The number is infinite. Unfortunately, however, it is still only an infinitesimal fraction of the number of response functions which may exist. We cannot simply select at random a set of filters, however numerous, and find appropriate constants for the equations, because these have to be true at an infinite number of wavelengths. In practice, of course, mathematical fulfilment of the condition is not necessary: practical tolerances exist within which errors are insignificant. Nor have we to consider an infinite number of wavelengths, for we can rely on a reasonable degree of continuity in physical properties and confine attention to a finite number of wavelengths, 30 or so, distributed throughout the spectrum. Even with these simplifications, however, there is no straightforward solution with any reasonable number of filters. They cannot be chosen at random, but have to be adjusted by variation of their constituents until the necessary conditions are fulfilled with sufficient accuracy at all parts of the spectrum.

Further, although in principle the problem is more easily soluble the greater the number of variables we introduce, in practice the attempt to adjust too many independent quantities leads to difficulty and confusion. There is little doubt that as far as the problem of filter construction is concerned a sufficiently close approximation to the requirements of an objective colorimeter could be obtained with not more than about six filters. The only reason why such instruments have not already been perfected is that thermopiles or other non-selective receivers are not sufficiently sensitive for this kind of work and photoelectric cells are not yet sufficiently reproducible in their spectral response functions. A set of filters developed to fit the spectral response of a particular cell would not suit another cell of the same nominal type. Every instrument would require filters developed to suit its own cell—a prohibitive requirement for commercial instruments. These practical difficulties will no doubt be overcome, either by development of more sensitive receivers of the non-selective types or of photocells with constant and reproducible spectral characteristics, and the physical measurement of light in all its aspects will become an established technique both of the photometrist and colorimetrist, who by that time will have become indistinguishable.

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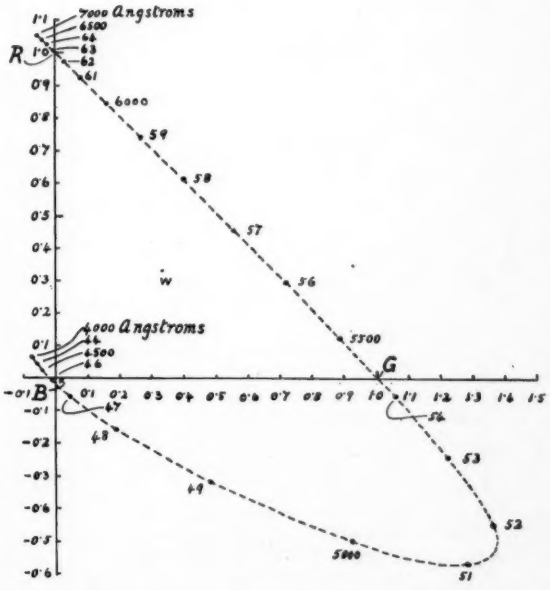

Fig. 1.—Spectral Locus on Colour Chart for the Red, Green and Blue standards of a particular trichromatic colorimeter (N.P.L., OP.1.250.)

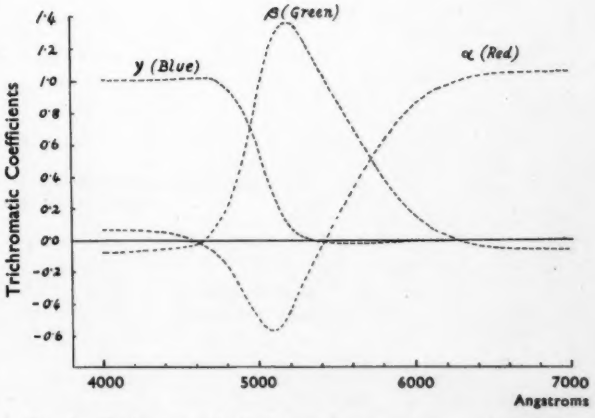

Fig. 2.—Trichromatic Coefficients of Spectrum in terms of the Red, Green and Blue standards of Colorimeter N.P.L., OP.1.250.

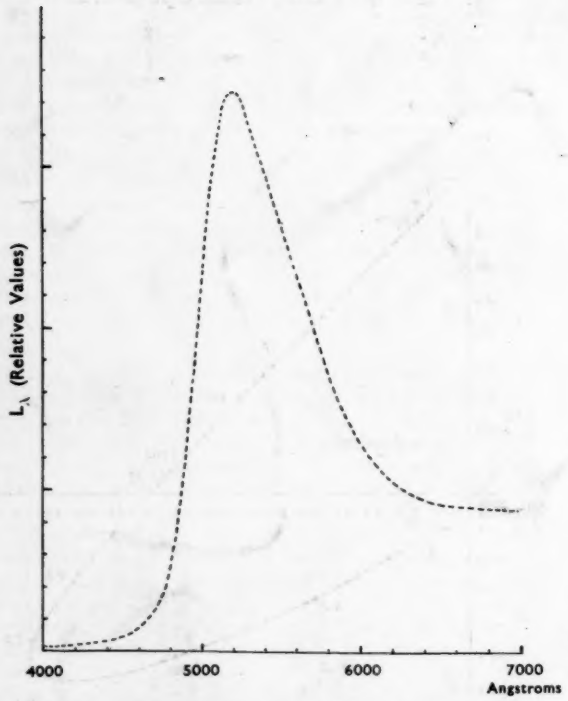

Fig. 3.—Relative Luminosity of a Trichromatic unit of monochromatic light throughout the spectrum for Colorimeter N.P.L., OP.1.250.

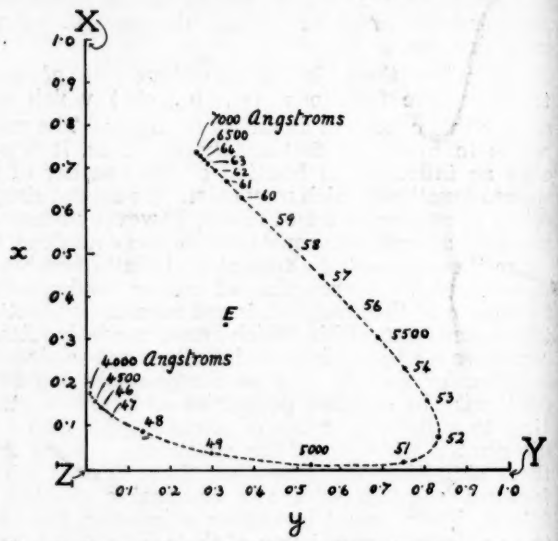

Fig. 4.—Spectral Locus on Colour Chart for the reference standards X, Y and Z of the C.I.E. system.

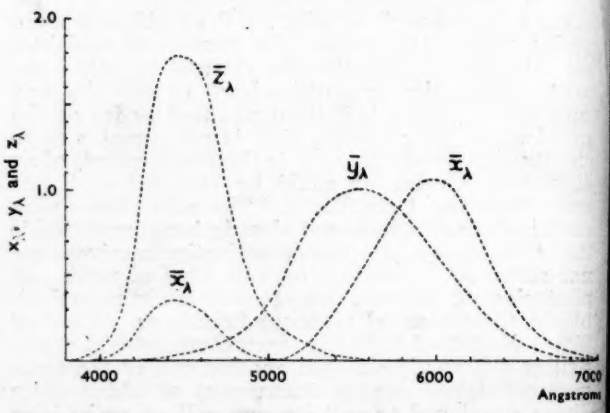

Fig. 5.—The "Distribution Coefficients" defining the C.I.E standard observer.

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